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Anisotropic Outflows and Enrichment of the Intergalactic Medium

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Abstract. We have developed an analytical model for the evolution of anisotropic galactic outflows. These outflows follow the path of least resistance, and thus travel preferentially into low-density regions, away from cosmological structures where galaxies form. We show that anisotropic outflows can significantly enrich low-density systems, while reducing the enrichment of overdense regions.

1. Introduction

Galactic outflows play an important role in the evolution of galaxies and the Intergalactic Medium (IGM). Supernova explosions in galaxies create galactic winds, which deposit energy and metal-enriched gas into the IGM. Simulations of explosions in a single object reveal that outflows tend to be highly anisotropic, with the energy and metal-enriched gas being channeled along the direction of least resistance (Martel & Shapiro 2001). Several observations also support the existence of anisotropic outflows both directly (e.g. Bland & Tully 1988; Veilleux & Rupke 2002) and indirectly (Pieri & Haehnelt 2004; Pieri, Schaye, & Aguirre 2006).

We represent outflows as two bi-polar spherical cones traveling along a path of least resistance, with an opening angle, α , that can vary from 180° (isotropic outflows) to $\sim 60^\circ$. The direction of these outflows is determined by the path of least resistance on the halo collapse scale. We describe the expansion of the outflows using the formalism of Tegmark, Silk, & Evrard (1993), modified for anisotropy. To implement this outflow model in a cosmological simulation, we use the Monte Carlo method of Scannapieco & Broadhurst (2001).

We track the formation of ~ 20000 galaxies in a comoving cubic volume of size $12h^{-1}\text{Mpc}$, in a ΛCDM universe. When these outflows strike halos in the process of collapsing, the outflows may ram-pressure-strip them of their baryons. Where the halo is not stripped, it is enriched by the metals carried by these outflows. The deposition of metals modify the cooling time of gas in halos and so the redshift of galaxy formation.

2. Results

To investigate the nature of the regions enriched in metals by outflows, we calculate the gas density and metallicity inside the computational volume, on a 512^3 grid (Pieri, Martel & Grenon 2006). The top panel of Figure 1 shows the

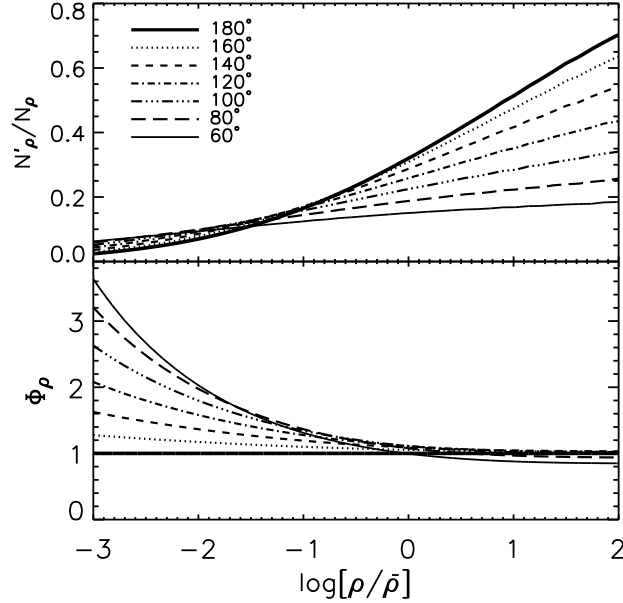


Figure 1. *Top*: fraction of enriched grid points N'_ρ/N_ρ in the simulation volume at $z = 2$ as a function of gas overdensity $\rho/\bar{\rho}$ for varying opening angle. *Bottom*: number of enriched points below an overdensity threshold, relative to the isotropic case.

number of grid points N'_ρ enriched at a given gas overdensity $\rho/\bar{\rho}$, as a fraction of the total number of grid points N_ρ at that density, for a range of different opening angles; this is effectively the probability of enriching a systems of a given density. The impact of galactic outflows on overdense systems is dramatically reduced for increasingly anisotropic outflows, while the probability of enriching low-density (around mean density of the Universe or lower) systems increases.

The bottom panel shows $\Phi_\rho = N'_{\rho' < \rho} / N'_{\rho' < \rho, 180^\circ}$, the number of enriched grid points with a overdensity below a given threshold ρ , relative to the isotropic case. This highlights the significant impact on the enrichment of underdense systems by anisotropic outflows. This can lead to an increase in the enriched volume of underdense systems of 10% (where $\alpha = 100^\circ - 120^\circ$) and an increase of 40% in systems below $\rho/\bar{\rho} = 0.1$ (where $\alpha = 80^\circ - 100^\circ$) compared to isotropic outflows.

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